Absolute Light Emission Efficiency of Crystal Anthracene for Gamma-Ray Excitation*

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The absolute light emission efficiency of crystal anthracene has been reported in the range from $\frac{1}{2}$ to 4 percent and in the vicinity of 10 percent. Further determinations involving integrated light intensity measurements are reported here, which give an efficiency of about 10 percent. The possibility of the discrepancies being due to the use of peak-height measurements in one set of experiments and integrated intensities in the others is discussed; preliminary experiments indicate that the difference in range of values is not due to this cause.

DISCREPANCIES of the order of ten for the absolute light output efficiency of anthracene or other organic crystals under gamma-ray excitation have been found reported in the literature.[1–5] (The relative light output is much more accurately known for the different organic materials.) The values given for the absolute efficiency may be divided into two groups, one ranging from between about $\frac{1}{2}$ percent to 4 percent and the other being in the vicinity of 10 percent. The measurements giving the lower range of values have been obtained using peak height determinations, whereas the larger values have been obtained with the integrated light output. The methods employed in some of the measurements were rather indirect; that reported by Harrison[2] used a "calibrated" photomultiplier.

On account of these differences, we have made a further determination of this efficiency. Only the integrated light output values were actually determined, but some information on the peak height efficiencies was also gained. Two methods were employed: 1. An indirect method—by comparing the light output of anthracene powder with that of ZnS powder and using the more or less accurate values known for ZnS. 2. A direct method—employing a photomultiplier and a calibrated thermopile and measuring the light output of both under the same geometrical conditions.

The first method was carried out by measuring the light output of powdered anthracene ($\sim$10 mg/cm^2) on a glass plate under alpha-particle excitation. The light emission of ZnS (Type D—du Pont, 10 mg/cm^2) was also obtained under identical conditions; their ratio was found to be about 50. Then, by using the known absolute α-particle efficiency of about 25 percent for ZnS, and the ratio[6,7] of $\sim$15 between gamma-rays and alpha-particles for the light output of anthracene for the same absorbed energy, the amount of absorbed gamma-ray energy which is converted into light was computed to be 7 percent.

The second, more direct and probably more accurate, method measured the light from a 5-mm illuminated spot on a blue oscilloscope screen with suitable glass filters (Corning) which transmitted light only in the same spectral region as the anthracene crystal. A thermopile and a photomultiplier were placed at the same distance from the light source, and the emitted light was measured with both. A set of film neutral filters which were independently calibrated by two methods was used with the photomultiplier. Finally, a 5-mm anthracene flake at the same distance from the photomultiplier was excited by a 1-mC gamma-ray source (radium), and its light emission was measured. From the calculation of the amount of energy absorbed by the crystal in unit time by the measured mass of anthracene,[8] the efficiency was then determined by making use of the photomultiplier calibration. This measurement gave a value of 10 percent for the gamma-ray-to-light conversion efficiency of anthracene. These are close to the previously obtained value calculated by comparison with the light output of naphthalene.[5]

Although these experiments were carefully done, the values given above are only approximate, since sufficient repetitions were not made to give a more exact value. The major limiting factors are: (1) The differences in spectral distribution which exist between the calibration light from the oscilloscope screen and that of anthracene. This may not be very important, since the same spectral range was covered in both cases and the photomultiplier sensitivity does not vary very much in this blue region. (2) The amount of gamma-ray energy absorbed by the crystal was calculated rather than measured. (3) Another important source of error lies in slight differences in the geometry and in the solid angles of the incident calibrating light (oscilloscope screen spot) and the measured light (anthracene flake). This was minimized by using the same geometry and solid angle for both light sources. We feel that these limitations would not produce a large deviation, and, therefore, that the efficiency is actually close to 10 percent.

A possible explanation for these differences between

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[1] J. I. Hopkins, Rev. Sci. Instr. **22**, 29 (1951).
[2] F. B. Harrison, Nucleonics **10**, 40 (1952).
[3] R. C. Sangster, Massachusetts Institute of Technology Technical Report No. 55, January, 1952.
[4] R. L. Paul, Ph.D. thesis, University of Oregon (unpublished).
[5] Broser, Kallmann, and Martius, Z. Naturforsch. **4a**, 204 (1949).
[6] Extrapolation from the data of Taylor *et al.* gives about 15.
[7] Taylor, Jentschke, Rembley, Eby and Kruger, Phys. Rev. **84**, 1034 (1951).
[8] One roentgen is equivalent to 83 ergs/g.

the integrated and peak-height measurements would be the existence of a tail in the decay curve of a light flash of the anthracene crystal. Such a tail could produce a considerable addition to the amount of light when integrated output is measured but would not show up in the peak height determinations Preliminary measurements on anthracene and CsBr carried out by Grace Marmor Spruch, however, tend to show that the emission of anthracene observed for the period of 10 milliseconds does not have a tail sufficient to account for the difference.

As a check, experiments with CsBr(Tl) were performed. With this crystal the integrated intensity is about 2 to 3 times as great as that of the same mass of anthracene for gamma-rays; the peak heights with a 1-megohm output resistance are, however, less than one-half of the anthracene value.[9] The light output of CsBr(Tl) takes place over a much more extended period than that of anthracene; certainly some light is still emitted after one millisecond, and this could account for the difference in peak heights. With longer circuit time constants, the peak heights of CsBr were considerably greater than those of anthracene. With anthracene, as remarked above, such an effect has not been detected; nevertheless, a very small, but long-time phosphorescence, sufficient to account for the above discussed differences, may exist. There are indications that some long-time phenomena do occur with anthracene, since a small but noticeable gamma-ray phosphorescence has been found, and also an energy storage which can later be released by light and does not instantaneously decay.

[9] Bittman, Furst, and Kallmann, Phys. Rev. **87**, 83 (1952).

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Arbitrary Concentrations of Matter and the Schwarzschild Singularity

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A nonstatic solution of the Einstein gravitational equations representing a spherically symmetric cluster of radially moving particles in an otherwise empty space is obtained. While it has been presumed by Einstein that the Schwarzschild singularity is physically unattainable as matter cannot be concentrated arbitrarily, the present solution seems to show that there is no theoretical limit to the degree of concentration, and that the Schwarzschild singularity has no physical reality as it occurs only in some particular coordinate systems. Incidentally, it is shown that in case of spherical symmetry the condition of conservation of gravitational energy of an isolated system of fluid material is equivalent to the vanishing of pressure at the boundary.

1. INTRODUCTION

THE Schwarzschild field for a mass particle,

$$ds^2=-(1+m/2r)^4(dr^2+r^2d\theta^2+r^2\sin^2\theta d\varphi^2)+\frac{(1-m/2r)^2dt^2}{(1+m/2r)^2}, \quad (1)$$

has singularities at $r=0$ and $r=m/2$. While it is not unnatural to identify the singularity at the origin of the spatial coordinate system with the mass particle, the "Schwarzschild singularity" at $r=m/2$ (corresponding to the vanishing of g_{44}) has been the subject of considerable speculation. Considering the field inside matter, Schwarzschild showed that if one considers an incompressible perfect fluid ($T_k{}^i=-p\delta_k{}^i$, for $i, k=1, 2, 3$; $T_4{}^4=\rho=$const.), such a singularity corresponding to the vanishing of g_{44} can indeed be attained if the size of a sphere of given density be sufficiently large. However, as pointed out by Laue, the assumption of incompressibility is not consistent with the ideas of the theory of relativity. In order to avoid this difficulty, Einstein[1] has more recently examined the problem by considering a spherically symmetric assembly of particles moving in randomly oriented circles around a common center and in arbitrary phases. From the condition that the geodesics of the particles must be time-like, Einstein finds that there is a limit to the degree of concentration of matter, and it then follows that if matter be introduced in this particular form, the Schwarzschild singularity is physically unattainable. Further Einstein has expressed the view that it is not "subject to reasonable doubt that more general cases will have analogous results." However, the following considerations throw doubts on this presumption and have led to the present investigation.

2. FUNDAMENTAL IDEA OF THE PRESENT PAPER

If one considers the cosmologic solution corresponding to a spherically symmetric cluster of particles falling

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[1] A. Einstein, Ann. Math. **40**, 922 (1939).